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APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

POWER SYSTEM ANALOG SIMULATION FOR A MOBILE LABORATORY

Prepared under Contract No. NAS8-11096 by

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For

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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ABSTRACT

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A simulation study analysis is performed on the Electric Power system for the Lunar Mobile Laboratory (MOLAB). Each subsystem and component is analyzed and related to the integrated system. Characterization of subsystem and components is performed utilizing simple electrical analogues to describe flows of heat, fluids, and gases as related to system observables and device parameters. The problems of logical control and decision in the area of the power distribution system are further defined and examined as related to automatic operation.

Author

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ASTRIONICS LABORATORY

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PREFACE

This report covers the work performed as Task Order N-48 by the Northrop Space Laboratories, Huntsville Department under contract NAS 8-11096 to the George C. Marshall Space Flight Center. The work herein represents the results of 20 man-week of effort, starting October 1, 1964, and terminating March 16, 1965.

The task covers a simulation study analysis of the electrical power system for a Lunar Mobile Laboratory. The NASA Technical Liaison Representative was Mr. E. E. Dungan of the Advanced Studies Office, Astrionics Laboratory. The task forms one of the current series of Apollo Logistics Support Systems studies assigned to the Huntsville Department of Northrop Space Laboratories.

SECTION 1.0

SUMMARY

A simulation study analysis is performed on the Electric Power System for the Lunar Mobile Laboratory (MOLAB).

The primary Chemical Electric Power System (CHEPS) consists of hydrogen-oxygen gas fuel cell modules, a Reactant Control System (RECS), a Thermal Management System (THEMS) and a Power Distribution System (PDS). The areas for investigation are as follows:

1. Formalization of thermal and electrical interior functions of hydrogen-oxygen fuel cells related to exterior input-output conditions and device parameters.
2. Formalization of thermal interior functions related to input-output condition for a double exchanger space radiator and a radioisotope generator of modified SNAP-19 configuration.
3. Definition and analysis of servo systems in the area of RECS.
4. Formalization of logical control aspects and "worst case" condition in the area of PDS.

In items one (1) through three (3) above it has been found that simple electrical analogues are effective in relating all observables to device parameters.

In item four (4) it is found that a trade-off may exist in the degree of automaticity of PDS control as related to human function and integrated system reliability.

SECTION 2.0

INTRODUCTION

Operational requirements have been placed upon the astronauts during the fourteen (14) day MOLAB lunar mission to perform functions related to observation, steering, navigation and communication. These functions reduce the budget of time that may be allotted to repetitive, laborious tasks or calculations of a routine nature. Periods of rest and sleep leave the vehicle unattended. The requirement arises for a high level of automaticity in the routine control and regulation of the fuel cell electric power system. Accomplishment of automatic fuel cell power management implies a thorough knowledge of all complex functional relationships involving system components and controlled variables during operational conditions.

SECTION 3.0

SCOPE

This study shall encompass an analysis of the simulation of each sensed and controlled variable of the MOLAB hydrogen-oxygen fuel cell electric power system. The electric power system shall consist of the following general areas for the purposes of analysis:

1. H_2 - O_2 Fuel Cell Modules.
2. Cryogenic reactants, tankage, and controls.
3. A space radiator.
4. A power distribution system.
5. A thermal management system.
6. Sensors and controls associated with the foregoing areas.

SECTION 4.0

PROBLEM DEFINITION

4.1 General - The continuous operation of the MOLAB electric power system demands the automatic regulation and control of numerous system functions. Accurate maintenance of system controlled functions under disturbances in load, environment and parameter variation and degradation form a general specification. In order to further define the effects of component and subsystem upon electric power system performance, an analysis of simulation is herein performed.

4.2 System Characterization - For the purposes of analysis and delineation of effort, it is convenient to divide the electric power system into specific problem areas. These areas may be enumerated as follows:

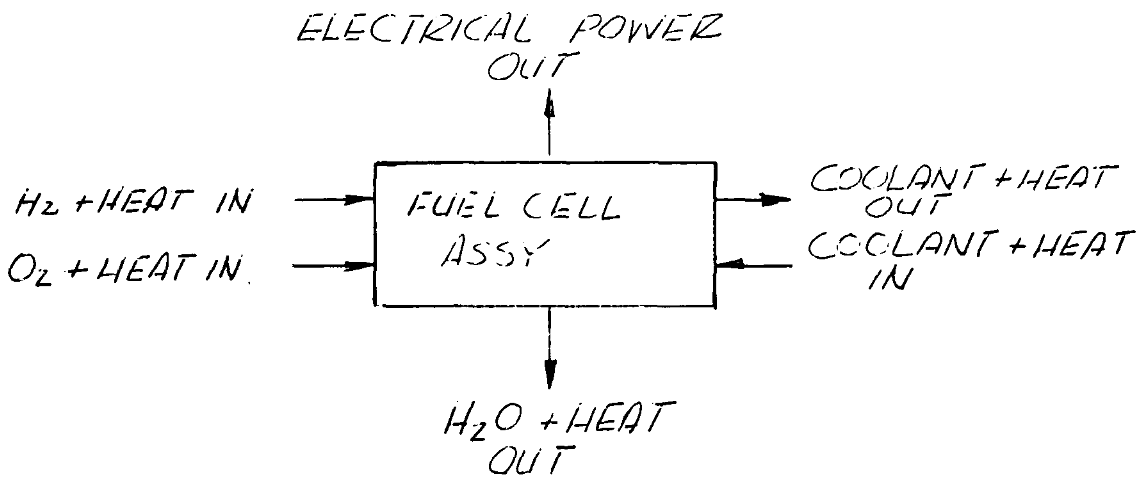
1. Fuel cell transfer functions
2. Reactant Control System transfer functions.
3. RTG transfer functions
4. Radiator transfer functions
5. Thermal Management Subsystem transfer functions
6. Power Distribution System
7. System Simulation

4.3 Component Analysis - Each area named above may be further delineated into components and interior functions. Individual components may be characterized by transfer functions, describing functions or sets of equations as may be applicable. Each area previously named in section 4.2 may interface with another and may transmit or receive a function transferred which may be gasdynamic, thermodynamic, fluid-dynamic, electrical, or of other form in nature.

SECTION 5.0

FUEL CELL TRANSFER FUNCTIONS

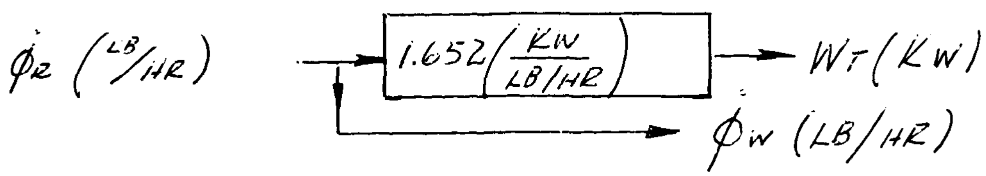
5.1 General - Characterization of a hydrogen-oxygen fuel cell proceeds from the relationships between input and output functions. This idealization is somewhat complicated by the presence of several input and outputs which are functionally cross-related. A schematic of inputs and outputs is presented as follows:



5.2 Energy Conversion - When two molecules of hydrogen and one molecule of oxygen combine, in a hydrogen-oxygen fuel cell, an exact specific amount of energy is released. The reaction $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ yields a potential of -1.229 volts under standard conditions. Total specific thermal and electrical power level for a given flow rate is:

$$W_s = 1.652 \text{ kw/(lb/hr)}$$

The ratio of hydrogen to oxygen mass flow rates is one to eight. Combination is considered taking place without delay. The following schematic relates reactant flow rates to total power and water production:



From the above, the control equations are:

$$W_T = 1.652\, \dot{\phi}_r$$

$$\dot{\phi}_w = \dot{\phi}_r$$

where $\dot{\phi}_r$ is the reactant flow rate in lbs. per hour, W_T is the total generated thermal plus electrical power level in kilowatts, and $\dot{\phi}_W$ is the water flow rate in lbs. per hour.

5.3 ELECTRICAL POWER

The total power, thermal plus electrical, produced by the fuel cell module is directly related to reactant flow rate by a constant as previously given in Section 5.2. The electrical power produced is therefore the total power produced less the power dissipated internally or:

$$W_e = W_T - W_D$$

The module efficiency is the ratio of electrical to total power which it:

$$\text{Eff} = 1 - \frac{W_D}{W_T}$$

The module efficiency unfortunately is not constant with changing electrical loads. A plot of voltage versus current exhibits a nonlinearity in the vicinity of light loads. The effects are said to be attributable to polarization losses. Regardless of nonlinearities however the total power generated is:

$$W_t = NE_iI \qquad (3)$$

Where N is the number of cells in the module, E_i the intrinsic voltage given in Section 5.2 and I is the current flowing. The electrical power in the load is of course

$$W_e = N\,E\,(I) \bullet I \qquad (4)$$

where N E(I) is the voltage across the load at a particular current I.

The efficiency therefore is:

$$\text{eff.} = \frac{W_e}{W_t} \qquad (5)$$

or:

$$\text{eff.} = \frac{E\,(I)}{E_i} \qquad (6)$$

Since the intrinsic cell voltage is 1.229 volts at STP, the efficiency of an H_2 - O_2 cell or module (independent of the number of cells) is

$$\text{eff} = .814\ E(I)$$

keeping in mind that E(I) is the voltage across the load due to a single cell in an assembly. This efficiency does not consider parasitic loads. In the region of normal cell operation a plot of E versus I can be approximated by a straight line with constant negative slope. If the E axis intercept is called E_o, and the slope is R_o, then the voltage per cell is given as:

$$E(I) = -R_o I + E_o \qquad (8)$$

The efficiency in the normal range of operation is:

$$\text{eff.} = .814\ (E_o - R_o I) \qquad (9)$$

Relating electrical power to flow rates of reactants as given in Section 5.2 gives:

$$W_e = (1.652)\ \dot{\phi}_r\ (.814)\ (E_o - R_o I) \qquad (10)$$

or specifically:

$$W_{es} = 1.34\ (E_o - R_o I)\ \ KW_e/\ (lb/hr)$$

The total internally dissapated power is:

$$W_D = (1\text{-eff})\ W_T, \qquad (12)$$

which in terms of flow rates of reactants is:

$$W_D = (1.652 - 1.34\ (E_o - R_o I))\dot{\phi}_r\ (KW) \qquad (13)$$

*also; $\dot{\phi}_r = K\ IN$ where $K = 7.45X10^{-4}\ \frac{lb}{hr}$ /ampere/cell

* (SEE REF. 1)

5.4 HEAT TRANSFER

As indicated by the schematic in 5.1 there are five heat flows contained in the idealization. These heat flows are enumerated as follows:

1. $\dot{Q}_h$, the heat flow rate associated with inflowing hydrogen,
2. $\dot{Q}_o$, the heat flow rate associated with inflowing oxygen,
3. $\dot{Q}_{ic}$, the heat flow rate associated with inflowing coolant,
4. $\dot{Q}_{oc}$, the heat flow rate associated with outflowing coolant,
5. $\dot{Q}_w$, the heat flow rate associated with outflowing water.

In order to maintain the operating temperature of the cell it is necessary that the summation of internal sources of heat rates and all external heat flow rates vanish i.e. $\dot{Q}_i = o$.

The inflow and internal heat rates are additive and the outflow heat rates are subtractive. The summation is given by:

$$W_D + \dot{Q}_h + \dot{Q}_o + \dot{Q}_{ic} - \dot{Q}_{oc} - \dot{Q}_w = o$$

Here W_D is the internal electrical dissipation.

Heat gains or losses by radiative transfer are considered as negligible due to superior device insulation.

Each of the heat flow rates given are related to the mass flow rates of either gas, water, or coolant. The relationships are as follows:

1. $\dot{Q}_h = R_h \, \Theta_h \, \dot{\phi}_h$
2. $\dot{Q}_o = R_o \, \Theta_o \, \dot{\phi}_o$
3. $\dot{Q}_{ic} = C_{pc} \, \Theta_{ic} \, \dot{\phi}_c$
4. $\dot{Q}_{oc} = C_{pc} \, \Theta_{oc} \, \dot{\phi}_c$

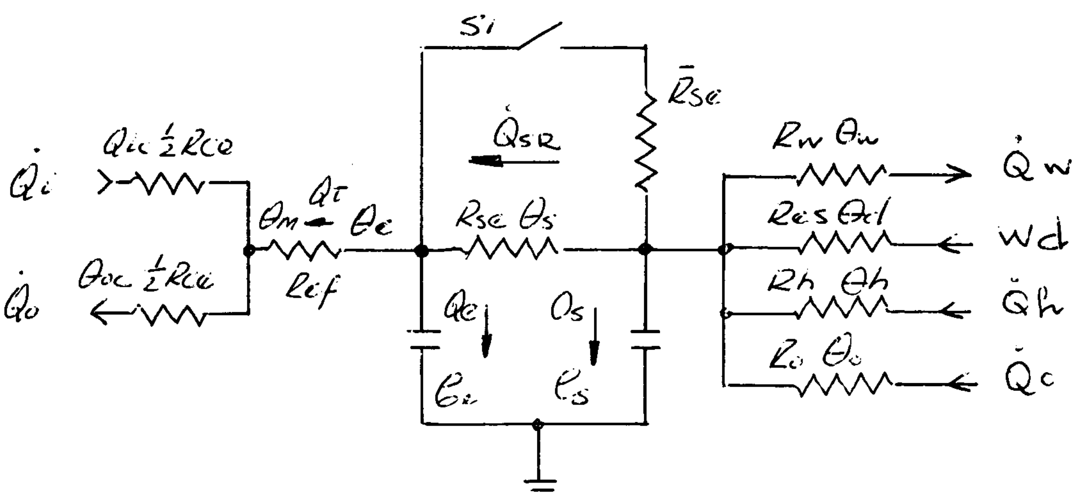
5. $\dot{Q}_w = c_{pw} \Theta_w \dot{\emptyset}_w$

The subscripted θ_s refer to the temperatures of the various substances whose mass flow rates are given by the subscripted $\dot{\emptyset}_s$. The subscripted R_s and C_s are respectively gas constants for the particular gas or the specific heat at constant pressure for the particular liquid. If steam, rather than water, is manufactured (depending upon cell temperature) then the multiplying constant for the water rate must be changed accordingly.

There are two additional auxiliary relationships, namely $\dot{\emptyset}_h + \dot{\emptyset}_o = \dot{\emptyset}_r$ and $\dot{\emptyset}_o = 8\ \dot{\emptyset}_h$.

The flows of liquid, gas and associated heat flow rates are modified by the presence of resistances to flow and associated storage capacities. In the case of liquids and gases the flows through resistance lend to pressure differences, and for heat flows, temperature differences. The following schematic illustrates the mechanisms involved:

LUMPED CONSTANT THERMAL MODEL



ACTIVE PHASE DEFINING EQUATIONS ($\theta_s \leqslant \theta_k + h$) (Sl is open)

1. $\dot{Q}_i + \dot{Q}_T - \dot{Q}_o = 0$
2. $\dot{Q}_{se} - \dot{Q}_T - \dot{Q}_e = 0$
3. $W_d + \dot{Q}_h + \dot{Q}_o - \dot{Q}_w - \dot{Q}_s - \dot{Q}_{se} = 0$
4. $\dot{Q}_{ic} = 2(\theta_{ic} - \theta_m)/R_{ce}$
5. $\dot{Q}_{oc} = 2(\theta_{oc} - \theta_m)/R_{ce}$
6. $\dot{Q}_T = (\theta_e - \theta_m)/R_{ef}$
7. $Q_e = j\omega \mathcal{C}_e \theta_e$

8. $\dot{Q}_{se} = (\theta_s - \theta_e)/R^*_{se}$

9. $Q_s = j\omega C_s \theta_s$

10. $Q_w = (\theta_s - \theta_w)/Rw$

11. $W_D = (\theta_{el} - \theta_s)/R_{es}$

12. $\dot{Q}_h = (Q_h - \theta_s)/R_h$

13. $\dot{Q}_o = (\theta_o - \theta_s)/R_o$

For the range $(\theta_s \geq \theta_R - h)$ switch Sl is closed and forced gas convection is taking place between the cell stacks and the exchanger.

During the dormant phase $\dot{Q}_w$, W_d, $\dot{\phi}_h$, $\dot{\phi}_o$ are zero and sl is open under all condition of θ_s.

The symbols shown above are defined as follows:

θ_{ic} = inlet coolant temperature
θ_{oc} = outlet coolant temperature
θ_m = effective film temperature
θ_e = heat exchanger temperature
θ_s = stack temperature
θ_w = water temperature
θ_o = oxygen inlet temperature
θ_h = hydrogen inlet temperature
θ_{el} = electrolyte temperature
R_{ce} = coolant effective thermal resistance
R_{ef} = coolant effective film thermal resistance
R_{se} = stack to exchanger thermal resistance, sl open
R^*_{se} = stack to exchanger thermal resistance, s2 closed.
R_w = water generation thermal resistance
R_h = hydrogen inlet thermal resistance
R_o = oxygen inlet thermal resistance

$\mathcal{C}_{he}$ - heat exchanger heat capacity

$\mathcal{C}_{s}$ = fuel cell stack heat capacity

Sl = a switch to provide the effect of a temperature controlled blower.

The dissipative input W_d may be provided from equation (13), Section 5.3. The reactant flows are provided in Section 5.2.

5.5 ANALYSIS SUMMARY

Each input quantity in the fuel cell area has been related to every output quantity which may consist of liquids, gases, heat and electrical power. All internal temperatures are defined relative to flow quantities and the constants of the device.

An examination of all applicable equations indicates the relationships which exist between the load current, which is the independent variable, and all other variables, which are dependent variables, to be rigidly determined by device parameters and physical considerations.

Each fuel cell manufacture utilizes a variety of mechanisms for the control and regulation of system variables such as gas pressure, stack temperature, and water separation and heat rejection. Analysis of regulation, from the standpoint of stability, is dependent to such an extent upon hardware that no analysis of these mechanisms is provided at this time. It is however felt that simulation of these equations may point to the appropriateness of the regulation of selected variables.

A reference drawing of a 2.2. KW fuel cell assembly showing connections is appended in Figure 1.

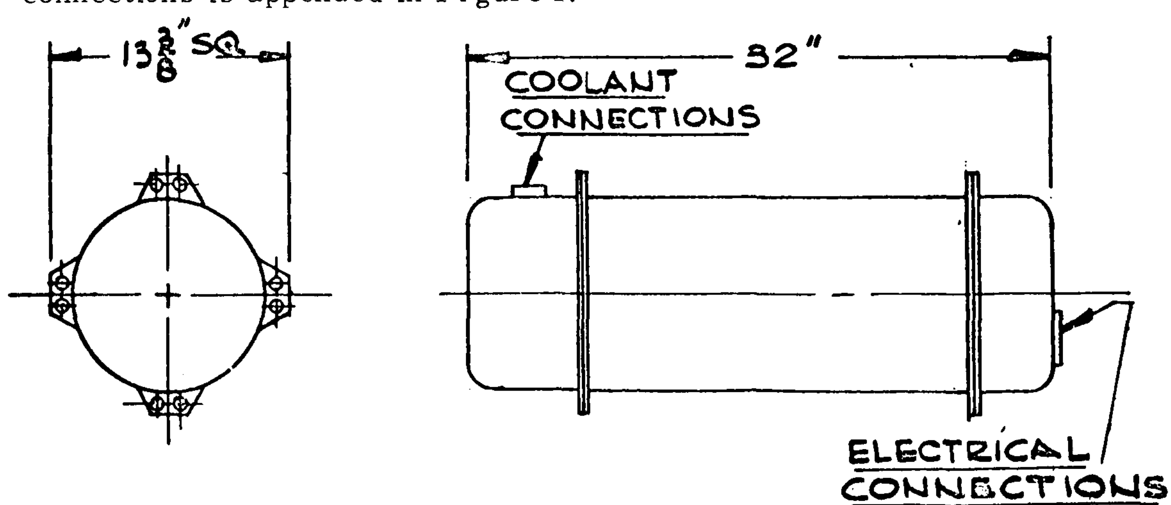


FIGURE 1. FUEL CELL ASSEMBLY

SECTION 6.0

REACTANT CONTROL SYSTEM (RECS) TRANSFER FUNCTIONS

6.1 GENERAL

The Reactant Control System under investigation in this section has been previously presented in the referenced literature (See Ref 2). The subject mechanization is shown in Figure 2. This system performs the functions of (1) storing the cryogenic reactants, namely liquid hydrogen and oxygen, (2) generation of gaseous hydrogen and oxygen from the liquids on a demand basis, (3) limiting tank pressures during storage by boil-off venting, (4) regulating tank pressures, and (5) regulating line pressures.

6.2 SYSTEM CHARACTERIZATION

Characterization of the Reactant Control System proceeds directly from relationships existing between output, input and intermediate functions. Attention is called to Figures 3 and 4 entitled "Hydrogen Sections Reactant Control System" and "Oxygen Sections Reactant Control System" respectively. Table 1 entitled "Reactant Control System Parameters" defines the nature of the parameters found in these figures.

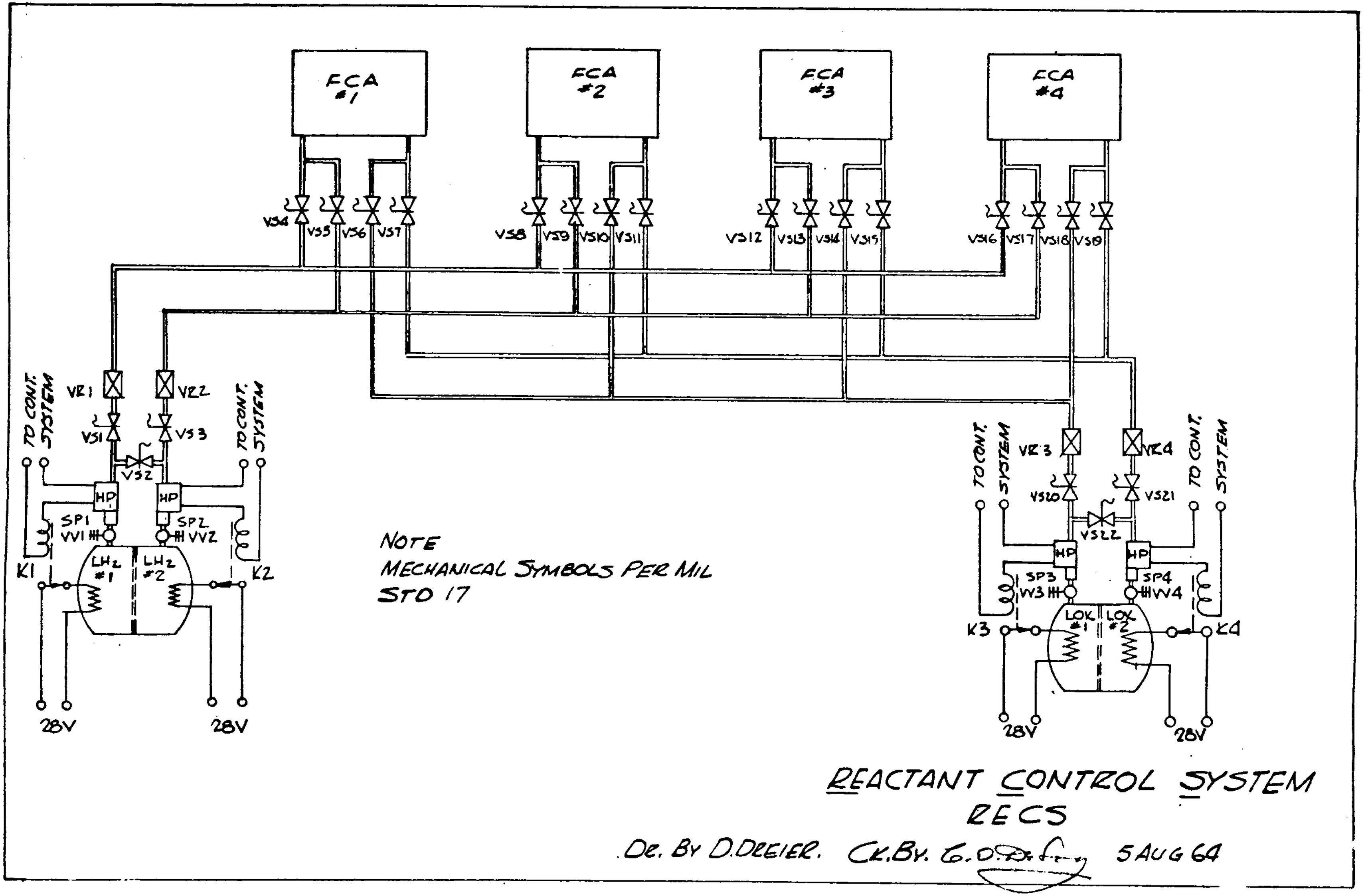
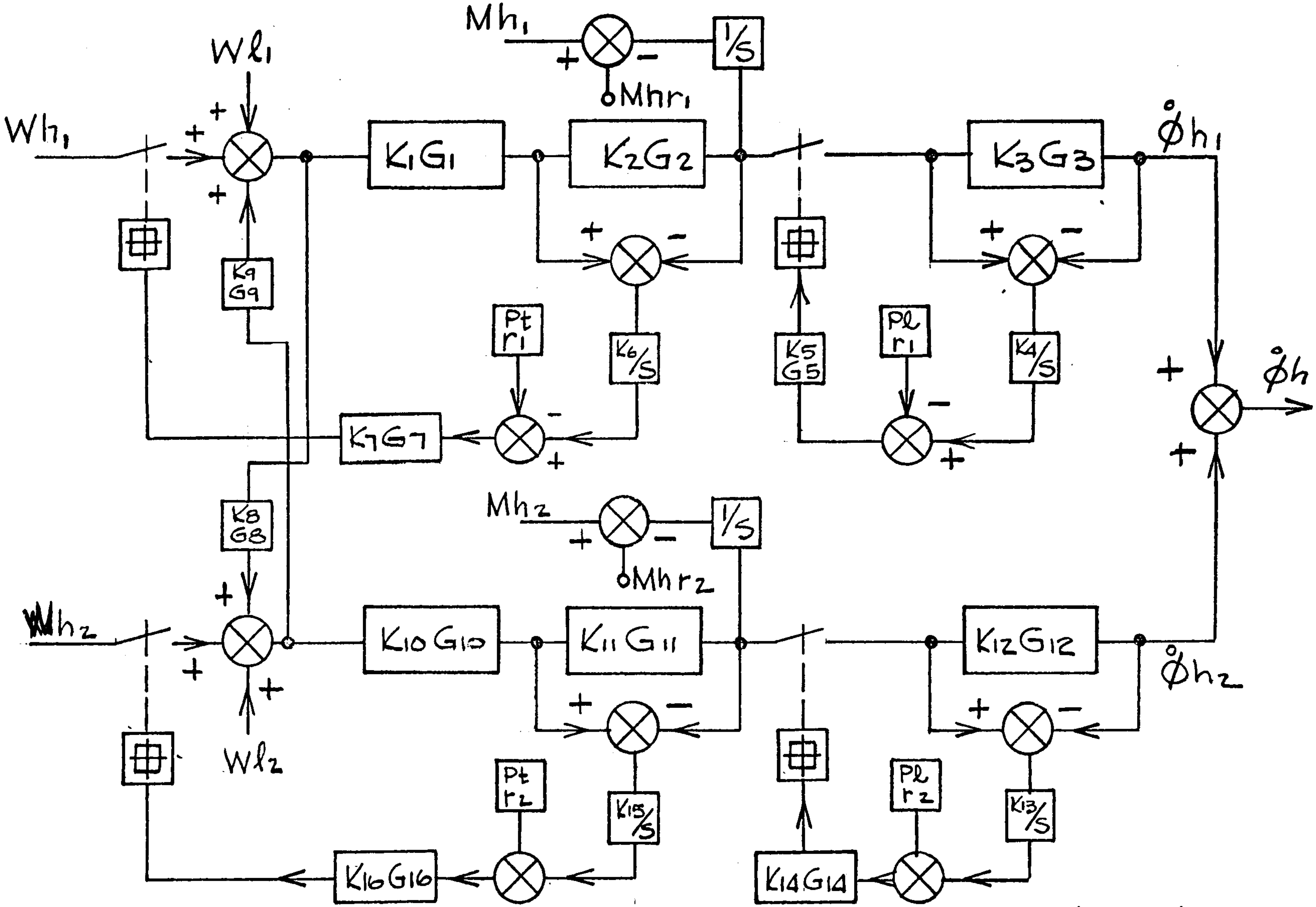
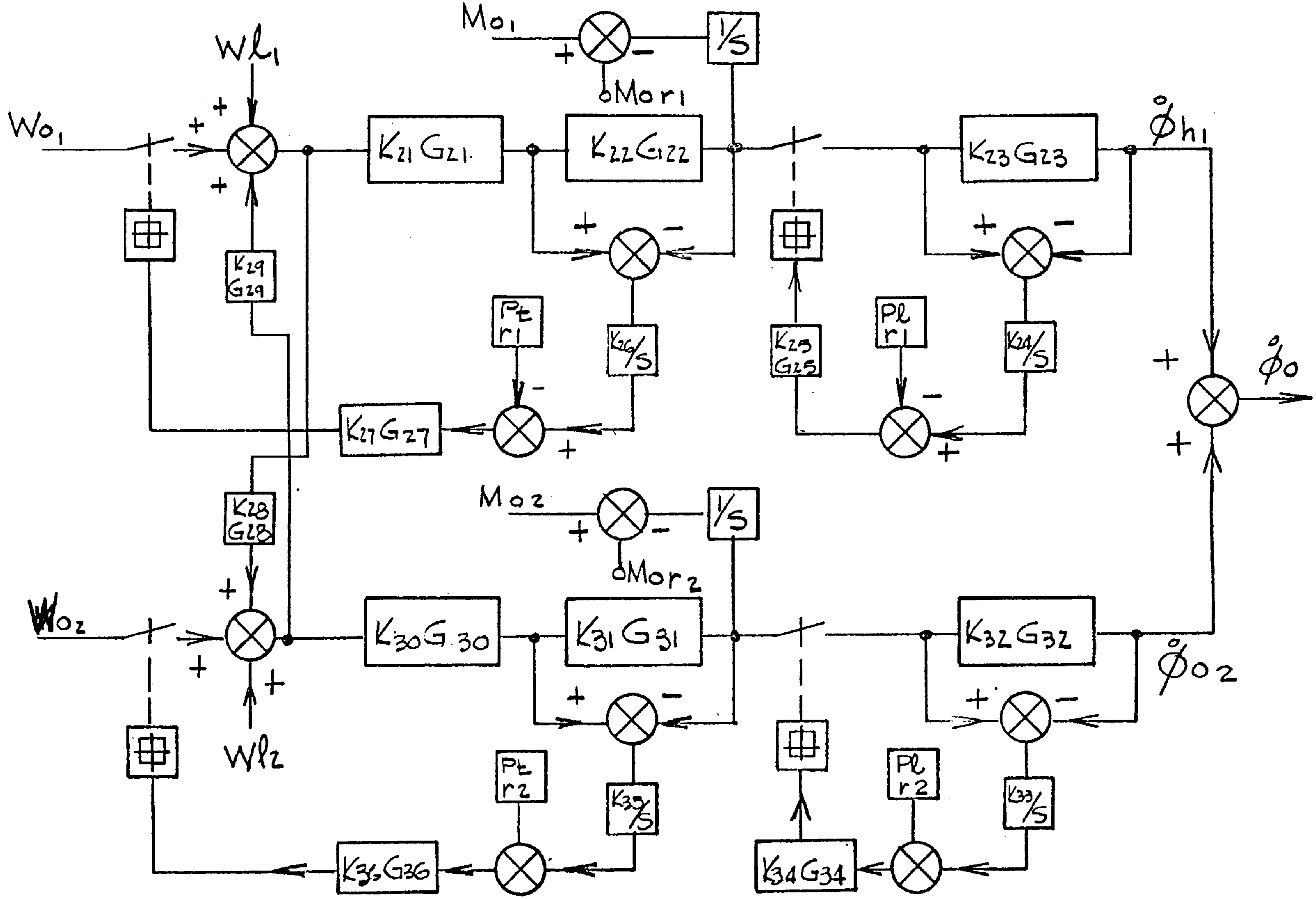


FIGURE 2. REACTANT CONTROL SYSTEM



HYDROGEN SECTIONS REACTANT CONTROL SYSTEM

FIG. 3



OXYGEN SECTIONS REACTANT CONTROL SYSTEM

FIG. 4

TABLE 1

REACTANT CONTROL SYSTEM PARAMETERS

K_1 = the number of lbs per hour of hydrogen produced at a given level of heater dissipation $\left(\frac{lb/hr}{KW}\right)$.

G_1 = $\frac{1}{1 + T_1S}$, where T_1 is the time constant related to the thermal resistance and heat capacity of the tank heater system.

K_2 = Unity

G_2 = $\frac{1}{1 + T_2S}$, where T_2 is the time constant related to tankage gas-dynamic capacity and resistance to flow

K_3 = Unity

G_3 = $\frac{1}{1 + T_3S}$, where T_3 is the time constant related to line gas dynamic capacity and resistance to flow.

K_4 = The number of lbs/sq-in pressure per lb of hydrogen gas stored in the piping at the operating line temperature.

P_{1R1} = the pressure reference of the pressure transducer in hydrogen line section No. 1 (lbs/sq-in)

K_5 = the number of lbs per hour of hydrogen which is caused to flow due to a particular pressure difference $\left(\frac{lbs/hr}{lb/sq\text{-}in}\right)$.

G_5 = $\frac{1}{1 + T_5S}$, where T_5 is the time constant of the pressure operated line regulator valve.

K_6 = the number of lbs/sq-in pressure per lb of gaseous hydrogen stored in the tankage at the operating gas temperature.

P_{TR1} = the pressure reference of the pressure transducer in hydrogen tank section No. 1 (lbs/in^2)

K_7 = the kilowatt level of heating caused to occur due to a particular pressure difference $\left(\frac{\text{kilowatts}}{\text{lb/sq. in.}}\right)$

G_7 = $\frac{1}{1 + T_7S}$, where T_7 is the time constant of the pressure operated heater switch.

Wl_1 = the incoming heat leakage rate through the hydrogen tankage section #1 walls due to exterior sources (KW)

Wh_1 = the tank #1 heater power level at nominal supply voltage (KW)

M_{h1} = the hydrogen tank #1 storage capacity (lbs of H_2)

M_{hR1} = the hydrogen tank #1 remaining hydrogen (lbs of H_2)

K_8 = the attenuation constant for heat rate of leakage into tank section #2 due to the heat rate in section #1 $\left(\frac{KW}{KW}\right)$

G_8 = $\frac{1}{1 + T_8S}$, where T_8 is the time constant due to the lag in transport of heat from tank section #1 to tank section #2.

K_9 = the attenuation constant for heat rate of leakage into tank section #1 due to the heat rate in section #2 (KW/KW)

G_9 = $\frac{1}{1 + T_9S}$, where T_9 is the time constant due to the lag in the transport of heat from tank section #2 to tank section #1.

Wh_2 = the tank #2 heater power level at nominal supply voltage (kilowatts)

Wl_2 = the incoming heat leakage rate through the hydrogen tankage section #2 walls due to exterior sources (KW)

ϕh_1 = the hydrogen rate of mass flow from section #1 (lbs/hr)

The remaining symbols, related to Section2, are defined exactly as their counterparts in Section 1 with the exception that the words "Section 2" are substituted for "Section 1" and vice versa.

The symbols relating to the oxygen sections are defined exactly as their functional equivalents in the hydrogen sections as previously given.

6.3 ANALYSIS SUMMARY

An analytical mechanization has been generated which, when supplied with operational constants in the range of applicable hardware, is capable of RECS simulation.

Effects of ambients temperatures on cryogenics containers is not a subject of this mechanization but rather inputs of heat from such sources. Cross flows of heat from one tank section to another are further considered as inputs and corresponding effects on the system may be examined. The total reactant flows may be summed and applied in the control equation referenced in Section 5.2 to generate total power produced. Reactant flow rates from individual tank sections may be combined as given in Section 5.4 to generate associated heat flow rates as inputs to individual fuel cells.

SECTION 7.0

RTG HEAT TRANSFER FUNCTIONS

7.1 GENERAL

The Radioisotope Thermoelectric generators (RTG) herein analyzed have been previously described in associated referenced literature (see ref.2). A drawing of the proposed item has been reproduced in Figure 5 for easy reference. Four (4) of these items are contained in the system under analysis and provide the four following functions on a redundant basis:

1. Provides a source of continuous heat to be utilized for component temperature conditioning during the dormant phase.

2. Provides a source of electric power for coolant pumping and distribution during the dormant and active phases.

3. Provides a primary source of power for system activation and telemetry transmission and reception during the dormant phase and a secondary source of power during the active phase.

4. Provides a source of heat for cabin conditioning and electric power for cabin coolant pumping during the active phase.

7.2 SYSTEM CHARACTERIZATION

The device under consideration is a SNAP-19 modified by the addition of coolant passages at the fin root. The unmodified SNAP-19 arrives at thermal equilibrium with its space environment by simple radiative heat transfer. Addition of cooling coils and coolant pumping allows heat to be extracted by forced convection. The fins, thus deprived of heat, do not radiate the total quantity of heat produced by the nuclear source. A balance is therefore arrived at dependent upon established coolant flow rates, ambient temperatures and heat production rates. For the purposes of analysis the production of heat can be assumed constant over the entire period of examination by utilization of PU-238 as a source material.

Since both the electrical and thermal output of these units remain constant during the entire period of operation, the area for investigation is in the variabilities of heat transfer induced by ambient temperature fluctuations and thermal demands.

The RTG units, as integrated into the system, interface with the thermal management subsystem (see Section 8.0) and the

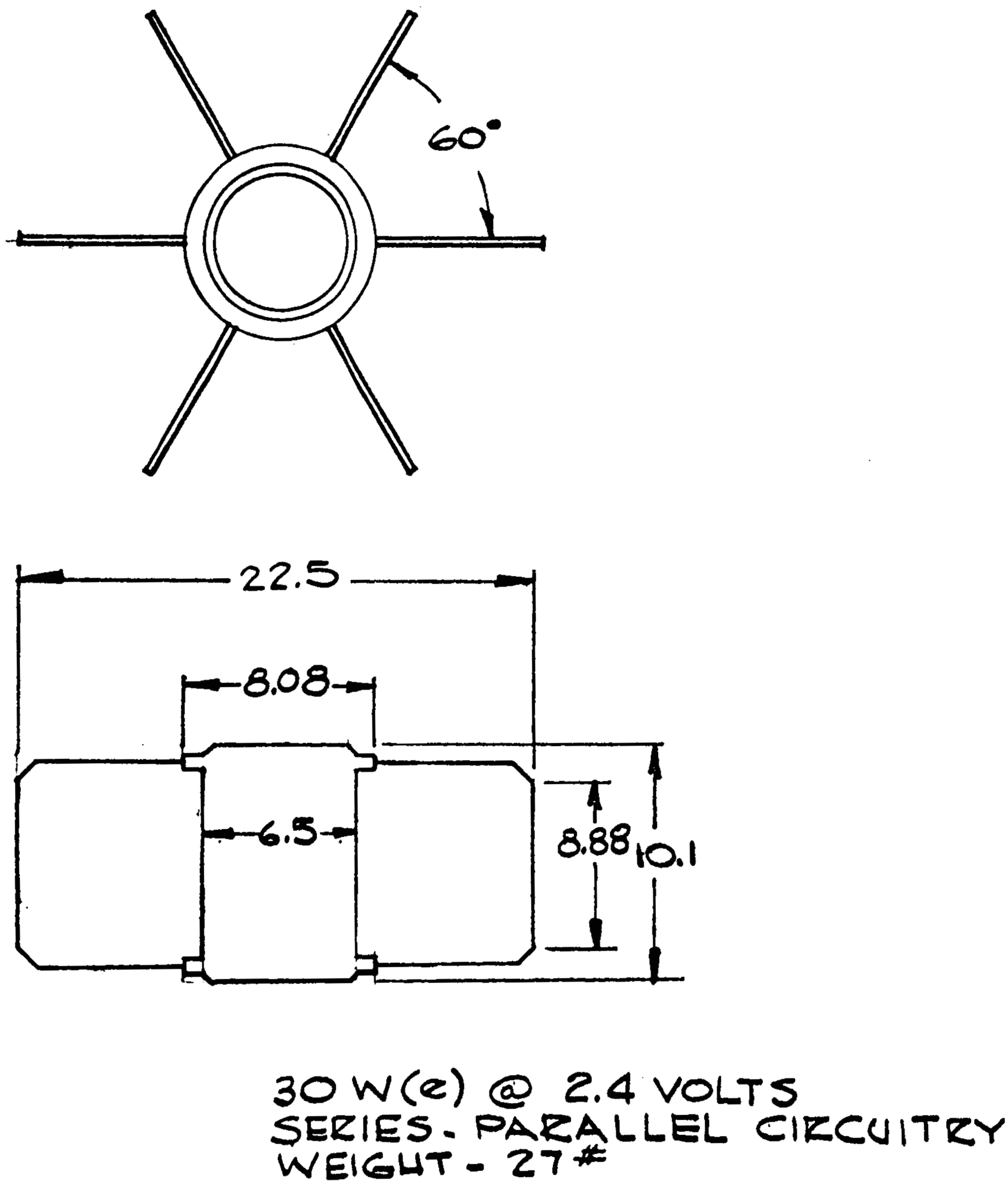
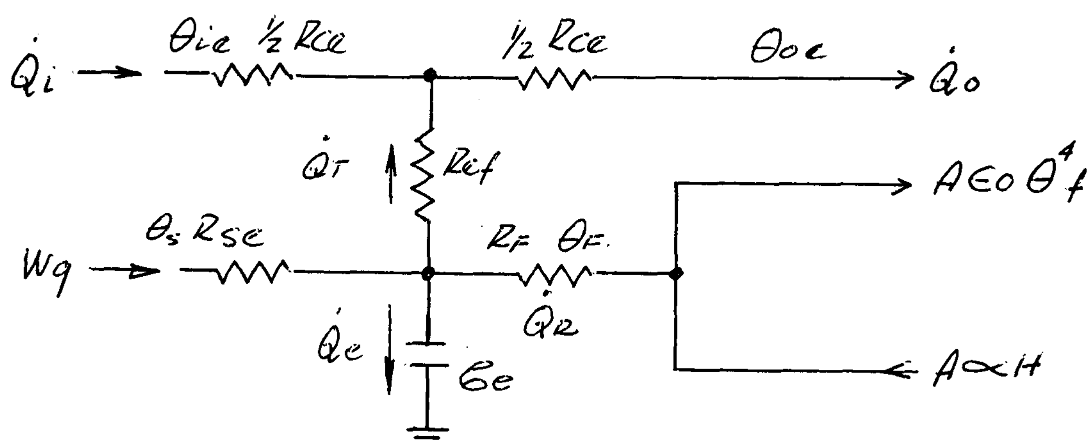


FIGURE 5. SNAP-19 THIRTY WATT GENERATOR

lunar environment. The amount of heat converted to electrical energy, approximately five per cent of the total heat generated, is considered to be negligible for analytical purposes.

In order to more readily characterize the RTG as a system element it is convenient to portray the operation by an electrical analogue. This can be easily shown as a lumped constant model.

LUMPED CONSTANT THERMAL MODEL



The symbols given in the above schematic are defined as follows:

$\dot{Q}_e$ = heat rate into the exchanger heat capacity,

$\dot{Q}_i$ = heat rate associated with the inlet coolant flow,

$\dot{Q}_o$ = heat rate associated with the outlet coolant flow,

W_g = heat rate generated by the decay of the nuclear source,

$\dot{Q}_R$ = heat rate to fin radiators

$\dot{Q}_T$ = heat rate across the film resistance

θ_f = fin temperature,

θ_{ie} = exchanger inlet coolant temperature,

θ_{oe} = exchanger outler coolant temperature,

θ_e = exchanger temperature,

θ_s = thermoelectric junction cold shoe temperature,

θ_m = effective film temperature

R_{ce} = coolant effective thermal resistance

R_{se} = shoe to exchanger thermal resistance

R_f = fin thermal resistance

R_{ef} = coolant effective film shunt thermal resistance

$\mathcal{C}_e$ = exchanger heat capacity

From an examination of the lumped constant thermal model, and the definitions of model parameters, it is seen that an analysis may be performed relating all observables. The defining equations are given as follows:

1. $\dot{Q}_i + W_g - \dot{Q}_R - \dot{Q}_e - \dot{Q}_o = 0$
2. $W_g - \dot{Q}_e - \dot{Q}_R - \dot{Q}_T = 0$
3. $\dot{Q}_T = (\theta_e - \theta_m)/R_{ef}$
4. $W_g = (\theta_s - \theta_e)/R_{se}$
5. $\dot{Q}_i = 2(\theta_{ie} - \theta_m)/R_{ce}$
6. $\dot{Q}_o = 2(\theta_{oe} - \theta_m)/R_{ce}$
7. $\dot{Q}_e = jw\mathcal{C}_e\theta_e$
8. $\dot{Q}_R + A\alpha H - A\epsilon\sigma\theta_f^4 = 0$
9. $\dot{Q}_R = (\theta_f - \theta_e)/R_f$

In the equations above the symbols ϵ and α are the values of emissivity and absorbtivity of the radiator effective area (A), σ is the Stephan-Boltzman constant, and H is the radiant heat flux rate.

A log-log plot of equation eight (8) showing total radiated power per unit radiator area versus fin temperature has been enclosed in Figure 6. The information shown may prove useful in scaling possible input program data and in estimating radiator area requirements for various inputs and outputs.

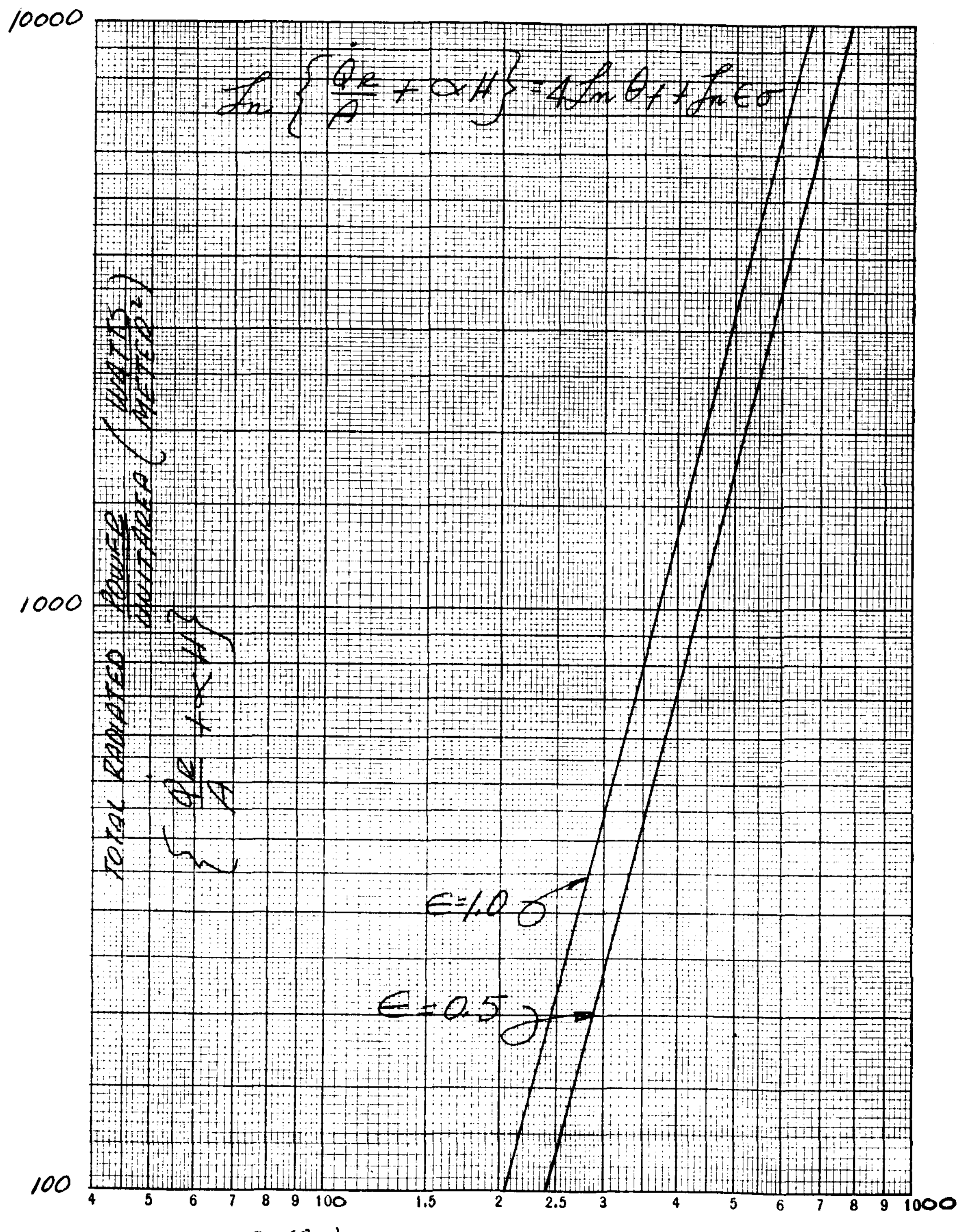


FIG 6 TOTAL RADIATED POWER FLUX VS FIN TEMP.

7.3 ANALYSIS SUMMARY

The four (4) major functions of the RTG units have been enumerated. A physical description of the device and its interface have been provided. A simple mathematical model relating all observable quantities has been generated which is adequate to perform simulation of the device as may be required.

SECTION 8.0

RADIATOR TRANSFER FUNCTIONS

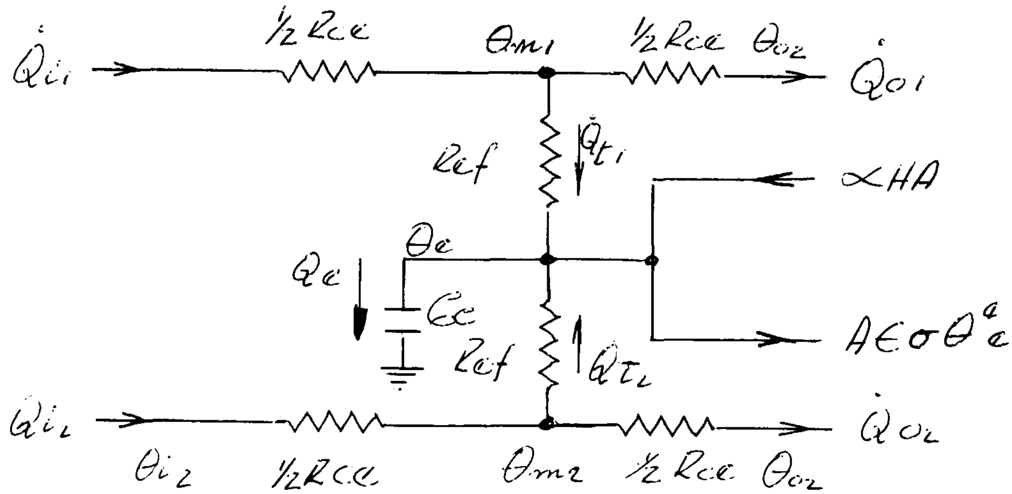
8.1 GENERAL

The system element, herein referred to as radiator, has been shown in previous literature (see Ref. 2) and interfaces with the Thermal Management System (see Section 9.0) as well as the Lunar thermal environment. This element performs the single function of rejection of fuel cell generated heat by means of radiation.

8.2 SYSTEM CHARACTERIZATION

The analysis of the radiator thermodynamics is very similar to the analysis developed in Section 7.0 covering the RTG. The only notable exceptions are in the absence of a nuclear heat source and the presence of a double exchanger with conductive mixing. The double exchanger has been innovated to isolate the seperate flows of exchange liquid from fuel cells, to add redundancy and therefore increase reliability. The injection of a double exchanger immunizes the system against total failure due to development of a single leak. The lumped constant thermal model follows directly from physical considerations.

LUMPED CONSTANT THERMAL MODEL



The symbols given in the above schematic are defined in terms of their physical counterparts, where the subscripts refer to section number one (1) or two (2) as may be appropriate. Definition of parameters follow:

$\dot{Q}_i$ = heat rate into the radiator via coolant inlet flow,

$\dot{Q}_o$ = heat rate out of the radiator via coolant outlet flow,

$\dot{Q}_T$ = heat rate across the coolant film,

$A \alpha H$ = rate into the radiator by radiant absorption from exterior sources,

$A \epsilon \sigma \theta_e^4$ = heat rate out of the radiator due to radiant emission,

$\dot{Q}_e$ = heat rate into the radiator heat capacity,

θ_i = inlet coolant temperature,

θ_o = outlet coolant temperature,

θ_m = effective film temperature,

θ_e = exchanger temperature,

R_{ce} = coolant effective thermal resistance,

$\mathcal{C}_e$ = exchanger heat capacity.

From the above schematic and given definitions it is seen that a set of equations may be generated which links all observables. The defining equations are given as follows:

1. $\dot{Q}_{i1} - \dot{Q}_{o1} - \dot{Q}_{T1} = 0$
2. $\dot{Q}_{i2} - \dot{Q}_{o2} - \dot{Q}_{T2} = 0$
3. $\dot{Q}_{T1} + A\alpha H - \dot{Q}_e - A \epsilon \sigma \theta_e^4 + \dot{Q}_{T2} = 0$
4. $\dot{Q}_{i1} = 2(\theta_{i1} - \theta_{m1})/R_{ce}$
5. $\dot{Q}_{o1} = 2(\theta_{01} - \theta_{m1})/R_{ce}$
6. $\dot{Q}_{12} = 2(\theta_{12} - \theta_{m2})/R_{ce}$

7. $\dot{Q}_{o2} = 2(\theta_{o2} - \theta_{m2})/R_{ce}$

8. $\dot{Q}_{T1} = (\theta_{m1} - \theta_e)/R_{ef}$

9. $\dot{Q}_{T2} = (\theta_{m2} - \theta_e)/R_{ef}$

10. $\dot{Q}_e = jw\mathcal{C}_e\theta_e$

8.3 ANALYSIS SUMMARY

A double exchanger radiator operating in an environment of exterior sources of radiant heat has been described. A simple model has been defined in terms of all observables by a set of ten (10) equations.

SECTION 9.0

THERMAL MANAGEMENT SYSTEM TRANSFER FUNCTIONS

9.1 GENERAL

The subsystem herein referred to as the Thermal Management System (THEMS) has been previously described in associated literature (see Ref.2). A schematic of THEMS is reproduced in Figure 7 for easy reference. This system performs the following functions.

1. Maintains the temperature of fuel cells, radiator, electronics temperature control plate, coolant and piping above specific preset temperatures during the six month dormant period.

2. Provides a means for rejecting fuel cell generated heat during the active period.

3. Provides a means for cabin heating during the active and dormant periods.

9.2 SYSTEM CHARACTERIZATION

The area of immediate interest for analysis involves the flow of heat through THEMS system elements and related temperatures ensuing therefrom. THEMS interfaces thermodynamically with heat flows leaving and entering the fuel cell assemblies. These heat flows have previously been analytically described under Section 5.0. THEMS further interfaces with the lunar thermal environments as well as cabin thermodynamics, RTG coolant loops (described in Section 7.0), and radiator (described in Section 8.0).

Attention is directed to figure seven (7) entitled "THEMS Simulation - Dormant Phase". The paths of fluid flow are descriptive of conditions prevalent during the dormant mode of operation. Each system element, previously described in Sections 5, 7, and 8, interfaces upon another in the manner as shown. Equality of output function and interface input function may readily be observed. A series of identical temperature operated valves is associated with fuel cells and radiator. Devices within the cabin bulkhead are not described although a double exchanger temperature plate may be envisioned as indicated in Figure six (6). Each temperature operated valve may possess a temperature reference, sensor, comparator, gain and hysteresis as indicated. In the case of an FCA* the stack temperature is the measured quantity, whereas the radiator exchanger temperature is regulated. Functions numbered one (1) and three (3) in Section 9.1 are provided during this operational mode.

* Fuel Cell Assembly

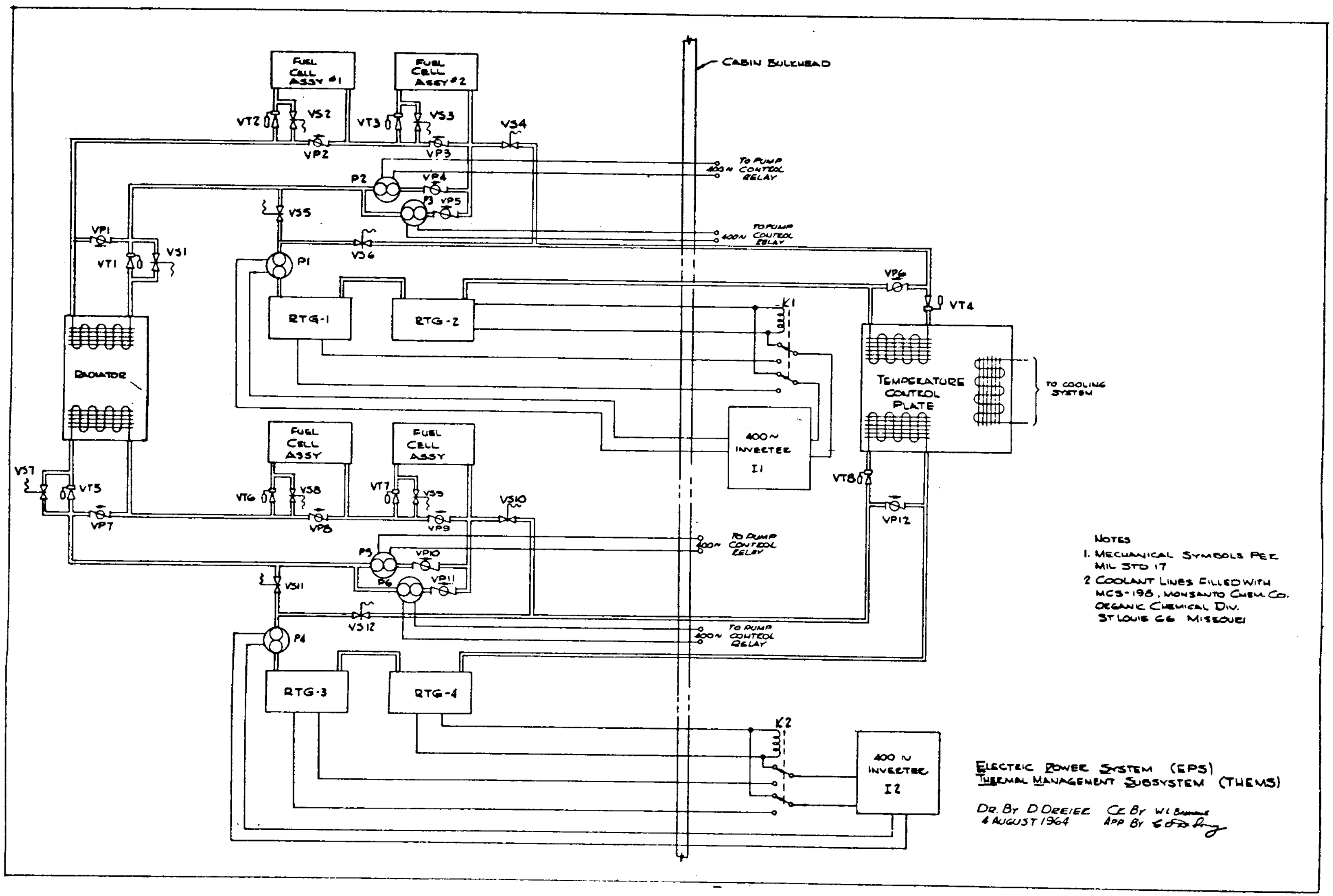
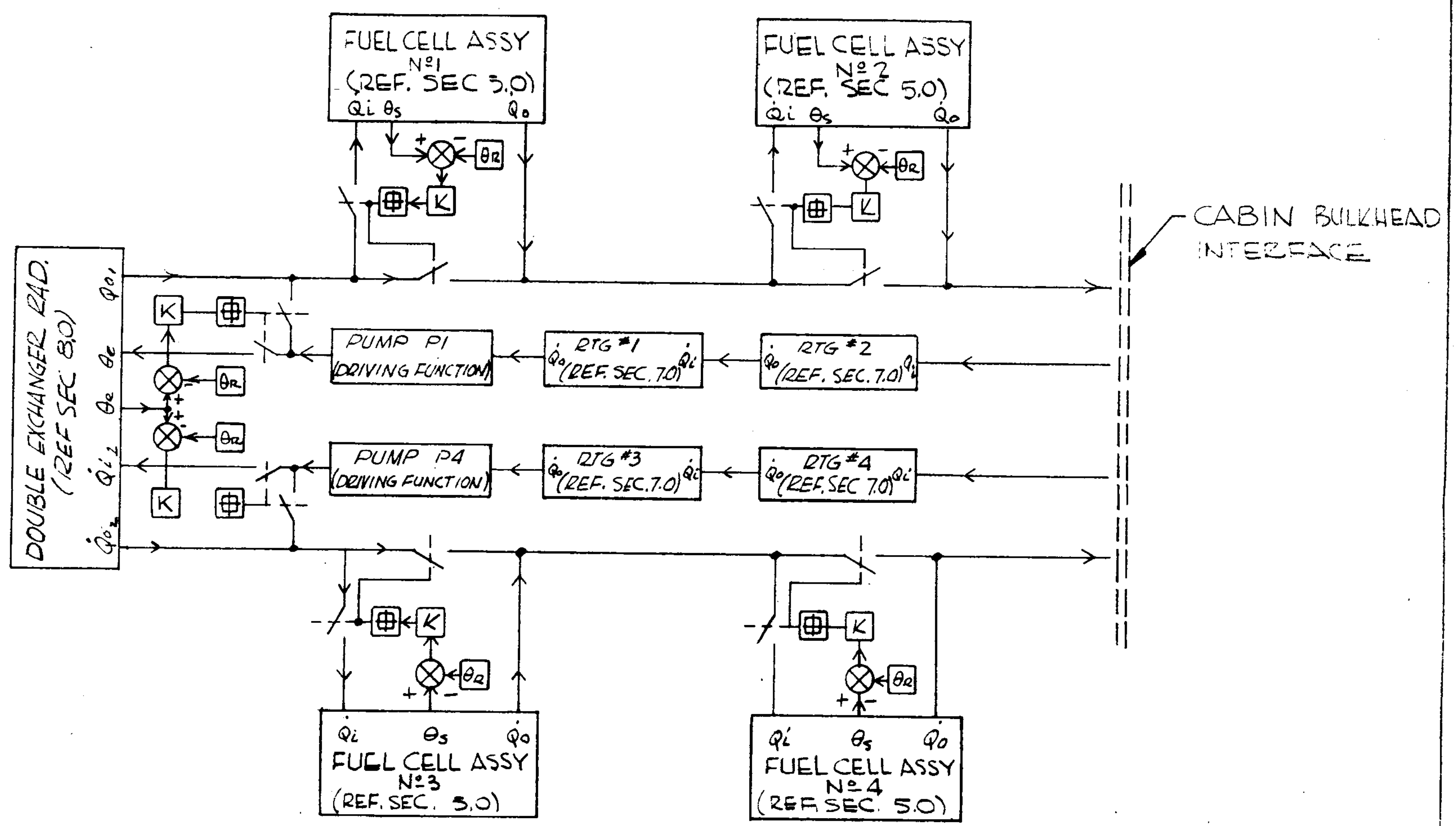


FIGURE 7. ELECTRICAL POWER SYSTEM THERMAL MANAGEMENT SUBSYSTEM

Figure eight (8) entitled "THEMS Simulation - Active Mode". This schematic is illustrative of fluid flow conditions, which imply forced convective heat transfer, that prevail during active power production. Note that flow loops through RTG units close on the cabin bulkhead and thereby satisfy function three (3)(ref. Section 9.1) during activation. Subsystem blocks representing RECS and PDS are added to imply active participation during this mode. The nature of the PDS interface with sources and loads is fully described in Section 10.0.

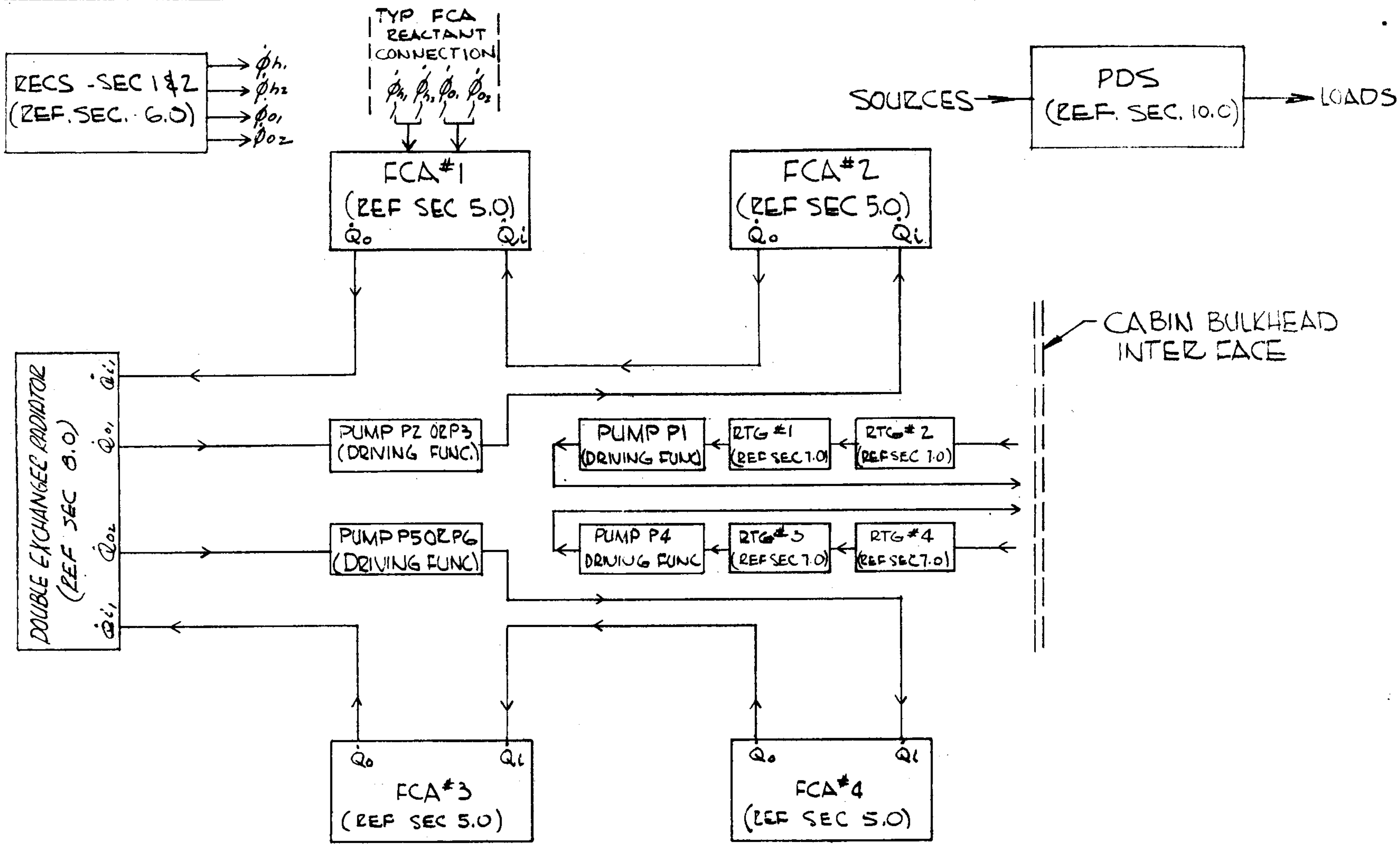
9.3 ANALYSIS SUMMARY

The three (3) major functions of THEMS have been defined. A system characterization has been involved which relates THEMS subsystem blocks during the active and dorman modes. The equality of output quantities interfacing on input quantities has been described.



THEMS SIMULATION DORMANT PHASE

FIG 8



THEMS SIMULATION ACTIVE PHASE

FIG 9

SECTION 10.0

POWER DISTRIBUTION SYSTEM (PDS)

10.1 GENERAL

The power distribution system herein analyzed has been previously described in the referenced literature (see ref. 2) A schematic is reproduced and addended in Figure 10.

The functions performed by this system are enumerated as follows:

1. Control the flow of power between:

   (a) each power source and each primary buss,

   (b) each primary buss and each secondary buss,

   (c) each primary buss

2. Establish a division of loads between:

   (a) each fuel cell and each primary buss,

   (b) each RTG and each primary buss.

3. Establish a protection system to protect from overcurrent:

   (a) each fuel cell assembly,

   (b) each RTG,

   (c) each secondary buss and associated equipment

10.2 SYSTEM CHARACTERIZATION

10.2.1 Logical Description

In order to facilitate further logical control of the power distribution system the entire network may be first described as a set of logical equations. Adopt the following symbols to indicate the presence of given currents and switch closures:

1. A, B, C, D, correspond to currents from FCA numbers one through four,

2. E, F, G, H correspond to currents from RTG numbers one through four,

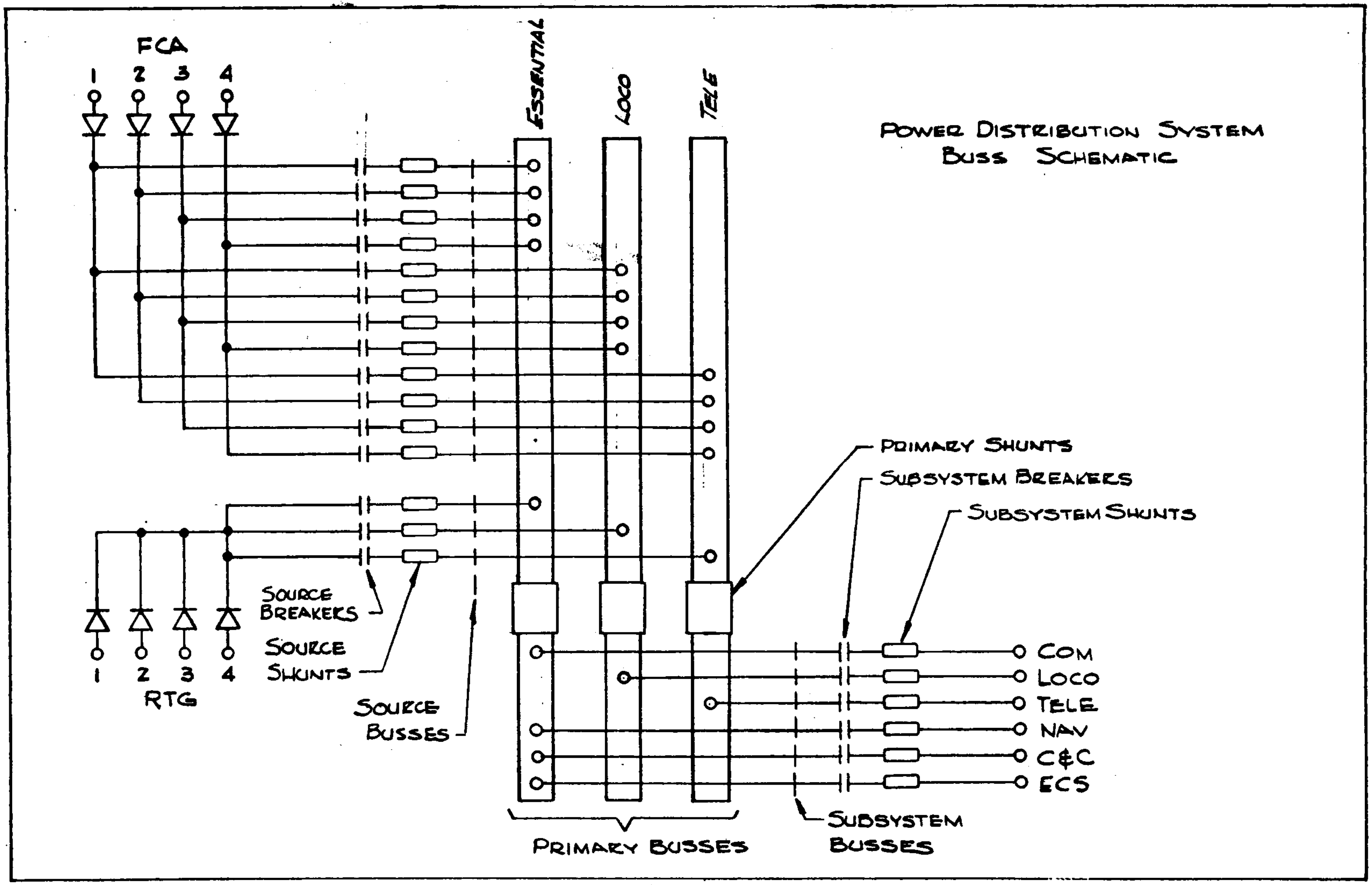


FIGURE 10 POWER DISTRIBUTION SYSTEM BUSS SCHEMATIC

3. M, N, O correspond to currents in the essential, locomotive and telemetry busses respectively,

4. R, S, T, U, V, W correspond to currents in the Com., Loco., Tele., Nav., C & C, and ECS secondary busses respectively.

5. P_1 through P_{12} designate closures of the twelve switches associated with the FCA units reading from top bottom in the referenced schematic

6. P_{13} through P_{15} designate closures of the three switches associated with the four RTG units reading top to bottom in the referenced schematic

7. P_{16} through P_{21} designate closures of the six switches associated with the six subsystem busses reading from top to bottom in the referenced schematic.

Combinative notation is that a dot (·) indicates an function and a plus (+) indicates an "or" function.

The presence of essential, locomotion, and telemetry buss currents are compounded consecutively as follows:

$$M = A \cdot P_1 + B \cdot P_2 + C \cdot P_3 + D \cdot P_4 + (E+F+G+H) \cdot P_{13}$$
$$N = A \cdot P_5 + B \cdot P_6 + C \cdot P_7 + D \cdot P_8 + (E+F+G+H) \cdot P_{14}$$
$$O = A \cdot P_g + B \cdot P_{10} + C \cdot P_{11} + D \cdot P_{12} + (E+F+G+H) \cdot P_{15}$$

From the above combination and the previous defintion the presence of subsystem buss currents, as previously named, are compounded as follows:

$$R = \{A \cdot P_1 + B \cdot P_2 + C \cdot P_3 + D \cdot P_4 + (E+F+G+H) \cdot P_{13}\} \cdot P_{16}$$
$$S = \{A \cdot P_5 + B \cdot P_6 + C \cdot P_7 + D \cdot P_8 + (E+F+G+H) \cdot P_{14}\} \cdot P_{17}$$
$$T = \{A \cdot P_9, + B \cdot P_{10} + C \cdot P_{11} + D \cdot P_{12} + (E+F+G+H) \cdot P_{15}\} \cdot P_{18}$$
$$V = \{A \cdot P_1 + B \cdot P_2 + C \cdot P_3 + D \cdot P_4 + (E+F+G+H) \cdot P_{13}\} \cdot P_{19}$$
$$V = \{A \cdot P_1 + B \cdot P_2 + C \cdot P_3 + D \cdot P_4 + (E+F+G+H) \cdot P_{13}\} \cdot P_{20}$$
$$W = \{A \cdot P_1 + B \cdot P_2 + C \cdot P_3 + D \cdot P_4 + (E+F+G+H) \cdot P_{13}\} \cdot P_{21}$$

As can be seen from examination of the above statements there are 2^{21} discrete states of connection due to the twenty-one breakers. Each subsystem buss, however, has only 2^6 connective states.

The source and subsystem breakers on the referenced schematic may be chosen to be relays which may be activated under a variety of circumstances. Criteria for activation may be developed which logically depend upon power system function and malfunction, as well as system normal and abnormal loads. These relays may be activated by manual override panel controls, in which case the operator must be supplied with a set of switching criteria which are the same as were supplied when formulating the control logic.

If the criteria for activation or inactivation of a particular relay or set of relays are selected to depend only upon source voltages and currents and load demands, under normal and abnormal conditions, the control loop may be non-complex in design. The control loop would interface only with the FCA and RTG outputs and the load inputs. This type of logical control may be designated as a "type I" logic Control System.

If, however, the criteria for relay activation are power system and load operationally oriented under normal and abnormal conditions and optimization processes are assumed, then the control loop may interface with many of the transducers which measure various quantities within the power system as well as the quantities measured in the "Type I" system. The criteria could be developed to, for example, connect the "right" FCA to the "right" load depending upon FCA performance and load level, change cryogenic tanks at run-out, increase purge-rate under module voltage drop-off, balance loads to minimize total reactant consumption, take reparative action under component malfunction, etc. This type of logical control system may be designated as a "Type II" logical control system.

10.2.2 Type I Versus Type II Logical Control

In the case of very high system reliability, where few, if any, malfunctions occur, the Type I system plus human operator is, for practical purposes, equivalent to the Type II system.

The time requirement on the human operator is minimum. The Type I logical control system reliability is high. The operator is supplied with an index of instructions equivalent to additional Type II logic which may be utilized under each possible failure mode. Failure mode may be indicated as audio or visual signals and operator action taken according to instruction index.

In the case of a power system of lesser reliability, a Type II system plus human operator might be utilized. A Type II system may contain more than an order of magnitude larger number of components than the Type I system. The number of in-line components is larger. Its reliability may be therefore less then the Type I system. Trouble shooting alarms due to false "no-go" signals may negate the operator time-saving gained by increased decision making logical complexity.

In summation it appears that a trade-off exists in control system selection which is dependent upon power system reliability, as an independent quantity, versus operator time and control system reliability.

10.3 POWER DISTRIBUTION SYSTEM TRANSFER FUNCTION

In reference to Section 10.2.1 a large number of possible transfer function combinations may exist. For the purposes of simulation, however, the "worst" case regarding regulation and transient responses is of greatest interest.

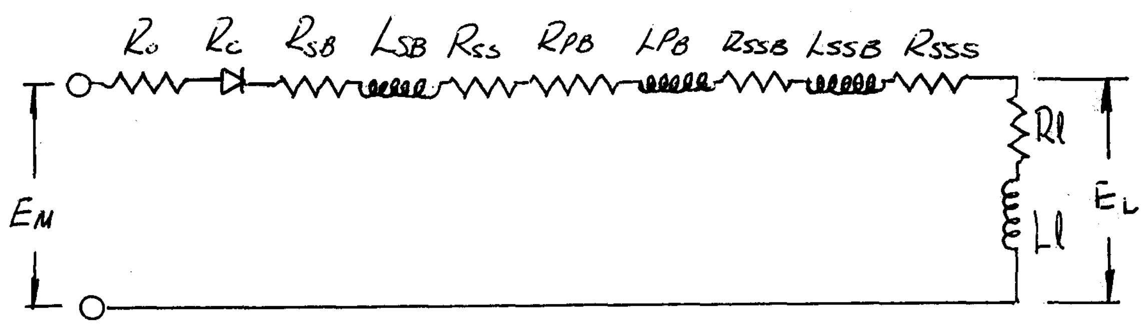
Several assumptions can be made to simplify the formulation without detracting from results. These assumptions are:

1. Due to low system voltages and high currents capacitive energy storage elements are negligible.

2. Inductive storage in shunts is negligible.

3. Diode junctions are sufficiently into the forward conduction region to present constant resistances.

The worst case for regulation is a single fuel cell as source, a single primary buss, a single source buss and a single subsystem buss. The schematic is presented as follows:



The transfer function for the above network is:

$$\frac{E_L}{E_M} = K \cdot \frac{(1 + \tau_2 S)}{(1 + \tau_1 S)}$$

Where: $$K = \frac{R_L}{\sum_i R_i}\quad , \quad S = jw$$

$$\tau_2 = \frac{L_\ell}{R_\ell} ,$$

$$\tau_1 = \frac{\sum_i L_i}{\sum_i R_i}$$

The symbols presented in the schematic above have the following meaning:

E_M	=	module voltage at light load,
E_L	=	the load voltage,
R_o	=	module internal resistance,
R_c	=	the resistance of a large area junction diode,
R_{SB}	=	the resistance of a source buss,
L_{SB}	=	the inductance of a source buss,
R_{SS}	=	the resistance of a source shunt,
R_{PB}	=	the resistance of a primary buss,
L_{PB}	=	the inductance of a primary buss,
R_{SSB}	=	the resistance of a secondary subsystem buss,
L_{SSB}	=	the inductance of a secondary subsystem buss,
R_{SSS}	=	the resistance of a secondary subsystem shunt,
R_ℓ	=	the resistance of the load
L_ℓ	=	the inductance of the load.
K	=	network gain at steady state

10.4 ANALYSIS SUMMARY

Characterization of a logical control system for the power distribution system has resolved to a choice of a Type I or Type II system. A reliability analysis may indicate the superiority of one type or the other as related to operator time and overall reliability.

The PDS has been resolved into a "Worst case" analysis in a particular switching condition. A Bode plot of the transfer function yields a tangent plot which starts with gain K at very low frequencies, has a break at $\omega_1 = \frac{1}{\tau_1}$ decreasing 20 db per decade out to another break $\omega_2 = \frac{1}{\tau_2}$ whereupon flat and continues at 20 db below the value K at higher frequencies.

SECTION 11.0

SYSTEM SIMULATION

11.1 GENERAL

Each subsystem block of the chemical electric power system has been discussed in previous sections and has been described in terms of observable quantities. A list of these quantities and applicable reference section has been prepared and is exhibited in Table 2.

TABLE 2

ELECTRIC POWER SYSTEM SIMULATION VARIABLES

ITEM	APPLICABLE SECTIONS
A. Fuel Cell Modules (Each Module)	5.0
1. Cell stack temperature	5.4
2. Module current	5.3, 10.3
3. Module voltage	5.3, 10.3
4. Hydrogen consumption rate	5.4, 6.0
5. Oxygen consumption rate	5.4, 6.0
6. Reactant Consumption rate	5.2, 6.2
7. Coolant inlet temperature	5.4
8. Coolant exit temperature	5.4
9. Coolant flow rate	5.4
10. Hydrogen inlet tamperature	5.4
11. Oxygen inlet temperature	5.4
12. Electrolyte temperature	5.4
13. Water generation rate	5.2
14. Water temperature	5.4
B. Cryogenic and Reactant Control System	6.0
1. Heater power	6.2, Table I
2. Reactant flow rate	6.2, Table I
3. Regulation inlet pressure	6.2, Table I
4. Regulator outlet pressure	6.2, Table I
5. Hydrogen remainant	6.2, Table I
6. Oxygen remainant	6.2, Table I
C. Radiator	8.0
1. Inlet Temperature	8.2
2. Outlet Temperature	8.2
3. Flow rate	8.2
4. Radiator temperature	8.2
5. Heat absorption	8.2
6. Total radiated power	8.2

TABLE 2 (cont'd)

ELECTRIC POWER SYSTEM SIMULATION VARIABLES

ITEM	APPLICABLE SECTIONS
D. Thermal Management Sybsystem	9.0
1. Main loop pump driving function	Fig. 8, 9.2
2. RTG loop pump driving function	Fig. 7, 9.2
3. Thermostatic valve operation	9.2
4. Bulkhead inlet and outlet conditions	Fig. 7, Fig 8
5. RTG inlet, outlet and fin temperature	7.2, 9.2
E. Power Distribution System	10.0
1. Source breaker positions	10.2.1
2. Subsystem breaker positions	10.2.1
3. Buss currents	10.2, 5.3
4. Buss voltages	10.3
5. Load voltages	10.3

In addition to the observable quantities listed in Table I which characterize system operation there are a large number of parameters which are further utilized to characterize the simple models presented. These parameters may be deduced by securing values of observables within the range of applicable operation. In not all cases are the parameters involved constant even within range of operation. In the case of resistance parameters utilized in forced convective flow, their values for example depend upon flow rate. If, therefore, the pumping rate is varied, then so must all such resistances in the system.

All parameters depend either strongly or weakly upon hardware design to such an extent that information regarding observables and operating conditions is mandatory prior to programming. It is, of course, necessary to scale all parameters prior to simulation. Due to the vary large number of parameters involved and overall complexity, it would be desirable to establish ranges of operation as well as ranges of parameter fluctuation prior to a simulation. This function can best be performed with a series of programs on a high-speed digital machine. From the results of hardware or device studies, and accumulation of applicable parametric data, and the results of digital program studies, it should then be possible to program meaningful simulation studies on an analogue machine.

11.2 CONCLUSIONS

Several conclusion occur as a result of the foregoing studies and are presented as follows:

1. Total system simulation of a complex lunar operational chemical electric power system can be achieved utilizing simple mathematical models of subsystem components.

2. Subsystem component simulation is dependent upon specific information relative to device parameters and observables applicable in typical ranges of interest.

3. Analogue simulation is dependent upon scaling and perturbation of device parameters and observables secured from digital programming.

11.3 RECOMMENDATIONS

Several recommendation may be presented and are enumerated as follows:

1. Prior to total system simulation a list of values of observables, specifically as shown in Table II, be accumulated relative to subsystem components preferably from laboratory demonstrable sources.

2. Digital programs be devised to perform perturbations on models determined by parameters secured under recommendation number 1 and to yield long term time-variant information.

3. Analogue programs be devised from information gathered under recommendation number 2 and to yield short term time-variant information.

REFERENCES

1. "Static Moisture Removal Concept for $H_2 - O_2$ Capillary Fuel Cell", Allis-Chalmers Research Division, Platner and Hess, Sept. 63

2. "Power System Conceptual Design", ALSS MOLAB Studies, NASA contract No. NAS8-11096, NASA CR 6102, October 64

APPENDIX A

A set of lists of ranges and increments of various constants and variables related to applicable areas are herein enclosed. Lists are conveniently delineated by component or subsystem. Each list supplies the symbol related to the analysis appearing in a previous section of this report as indicated. The units of measure, character, range and increment are supplied for each item symbol given. Values given do not represent limit tolerances but are ranges of typical cases.

FUEL CELLS
(Values Per Module), (Section 5.0)

ITEM	VALUE/RANGE	INCREMENT	UNITS	CHARACTER
W_S	1.652	--	kw/lb/hr	Constant
W_T	0 - 3.3	--	kw	Variable
$\dot{\phi}_W$	0 - 2.2	--	lb/hr	Variable
$\dot{\phi}_R$	0 - 2.2	--	lb/hr	Variable
W_e	0 - 2.2	--	kw	Variable
W_d	0 - 1.4	--	kw	Variable
E_{ff}	.50 - .80	--	Dimen-sionless	Variable
R_o	.002 - .003	.001	Volts/amp	Constant
I	5 - 85	5	Amps	Variable
E_o	.93 - .96	.01	Volts	Constant
K	7.45×10^{-4}	--	$\frac{lb/hr}{Amp/cell}$	Constant
N	32 - 35	1	No. of cells	Constant
$\dot{Q}_{ic}$	50 - 500	--	Watts	Variable
$\dot{Q}_w$	0 - 150	--	Watts	Variable
$\dot{Q}_{oc}$	0 - 1.4	--	Watts	Variable
$\dot{Q}_{se}$	0 - 1050	--	Watts	Variable

ITEM	VALUE/RANGE	INCREMENT	UNITS	CHARACTER
$\dot{Q}_h/\dot{\phi}_h$	(-) 0.66	--	kw/lb/hr	Constant
$\dot{Q}_o/\dot{\phi}_o$	(-) 0.029	--	kw/lb/hr	Constant
R_{ce}	.03 - .09	.01	^oK/watt	Constant
R_{ef}	.06 - .12	.01	^oK/watt	Constant
R_W	.13	--	^oK/watt	Constant
R_{es}	.014	--	^oK/watt	Constant
R_h	3.0	--	^oK/watt	Constant
R_o	6.8	--	^oK/watt	Constant
R_{se}	.40	--	^oK/watt	Constant
$\bar{R}_{se}$	.021	--	^oK/watt	Constant
R^*_{se}	.02	--	^oK/watt	Constant
C_e	1,000-5,000	1000	watt-sec/^oK	Constant
C_s	2,000-10,000	1000	watt-sec/^oK	Constant
θ_{ic}	200 - 500	--	^oK	Variable
θ_{oc}	320 - 600	--	^oK	Variable
θ_w	480	--	^oK	Variable
θ_{el}	520	--	^oK	Variable
θ_h	20	--	^oK	Variable
θ_o	90	--	^oK	Variable
θ_m	200 - 400	--	^oK	Variable
θ_e	480	--	^oK	Variable
θ_s	500	--	^oK	Variable

REACTANT CONTROL SYSTEM
(SECTION 6.0)

ITEM	RANGE	INCREMENT	UNITS	CHARACTER
K_1	20 - 100	10	lb/hr/kw	Constant
K_4	1×10^4 - 4×10^4	10^4	$lb/in^2/lb$	Constant
K_5	1.0 x 3.0	0.5	$\frac{lb/hr}{lb/in^2}$	Constant
K6	1.0 - 1.5	0.1	$lb/in^2/lb$	Constant
K_7	50 - 250	50	$kw/lb/in^2$	Constant
K_8	.05 - .15	.025	Dimensionless	Constant
K_9	.05 - .15	.025	Dimensionless	Constant
T_1	5 - 50	5	Seconds	Constant
T_2	.05 - .20	.02	Seconds	Constant
T_3	.01 - .05	.01	Seconds	Constant
$P_{\ell R1}$	20 - 50	5	lbs/in^2	Constant
T_5	.05 - .150	.025	Seconds	Constant
P_{TR1}	90 - 150	10	lbs/in^2	Constant
T_7	.010 - .10	.01	Seconds	Constant
$W_{\ell 1}$	.005 - .025	.005	kw	Variable
W_{h1}	50 - 250	50	kw	Constant
M_{h1}	80 - 125	5	lbs	Constant
W_{h2}	50 - 250	50	kw	Constant
$W_{\ell 2}$	.005 - .025	.005	kw	Variable
$\dot{\phi}_{h1}$	0 - .25	.05	lbs/hr	Variable

RADIOISOTOPE THERMOELECTRIC GENERATOR
(Section 7.0)

ITEM	VALUE/ RANGE	INCRE-MENT	UNITS	CHARACTER
W_g	0 - 1000	100	Watts	Variable
$\dot{Q}_i$	0 - 1000	100	Watts	Variable
$\dot{Q}_o$	0 - 1000	--	Watts	Variable
$\dot{Q}_r$	0 - 1000	--	Watts	Variable
$\dot{Q}_t$	0 - 1000	--	Watts	Variable
R_{ce}	.03 - 4.0	.01	^oK/Watt	Constant
R_{ef}	.01 - .10	.01	^oK/Watt	Constant
R_{se}	3.0×10^{-4} - 3.0×10^{-3}	3×10^{-4}	^oK/Watt	Constant
R_f	3×10^{-3} - 9×10^{-3}	10^{-3}	^oK/Watt	Constant
$\mathcal{C}_e$	1000 - 5000	1000	Watt-sec/^oK	Constant
θ_{ie}	116 - 475	20	^oK	Variable
θ_m	50 - 500	--	^oK	Variable
θ_{oe}	$\leq$ 500	--	^oK	Variable
θ_s	440 - 500	10	^oK	Variable
θ_e	440 - 500	--	^oK	Variable
θ_f	$\leq$ 500	--	^oK	Variable
A	$.0022\ W_g$ - $.0066\ W_g$	$10^{-4} W_g$	Meters^2	Constant

Radioisotope Thermoelectric Generator (Continued)

ITEM	VALUE/RANGE	INCRE-MENT	UNITS	CHARACTER
ϵ	.60 - .90	0.1	Dimensionless	Constant
σ	5.67×10^{-8}	--	$\frac{\text{Watts}}{\text{Meter}^2\text{-}^\circ\text{K}^4}$	Constant
α	.10 - .50	0.1	Dimensionless	Constant
H	0 - 1600	200	Watts/Meter^2	Variable

RADIATOR

(SECTION 8.0)

ITEM	VALUE/RANGE	INCRE-MENT	UNITS	CHARACTER
$\dot{Q}_i$	250 - 2500	100	Watts	Variable
$\dot{Q}_o$	50 - 500	--	Watts	Variable
$\dot{Q}_T$	200 - 2000	--	Watts	Variable
αH	0 - 1600	100	Watts/Meter^2	Variable
$\epsilon \sigma \theta_e^4$	200 - 2500	100	Watts/Meter^2	Variable
θ_e	250 - 400	--	^oK	Variable
θ_i	320 - 600	--	^oK	Variable
θ_o	200 - 500	--	^oK	Variable
θ_m	250 - 410	--	^oK	Variable
R_{ce}	.05 - .15	.01	^oK/Watt	Constant
R_{ef}	.01 - .06	.005	^oK/Watt	Constant
$\mathscr{C}_e$	1000 - 6000	1000	Watt-sec/^oK	Constant
A	5.0 - 15.0	1.0	Meter^2	Constant

POWER DISTRIBUTION SYSTEM
(SECTION 10.0)

ITEM	VALUE/RANGE	INCREMENT	UNITS	CHARACTER
E_M	30 - 32	--	Volts	Variable
E_L	24 - 32	--	Volts	Variable
R_o	.04 - .06	.005	Volts/Amp	Constant
R_c	.005	.001	Volts/Amp	Constant
R_{sB}	.005	.001	Volts/Amp	Constant
R_{ss}	.001	.0001	Volts/Amp	Constant
R_{PB}	.001	.0001	Volts/Amp	Constant
R_{ssB}	.005	.001	Volts/Amp	Constant
R_{sss}	.001	.0001	Volts/Amp	Constant
R_L	.30 - 1.8	.01	Volts/Amp	Variable
L_{SB}	$(.5\text{-}5) \times 10^{-6}$	10^{-7}	Volt-Sec/Amp	Constant
L_{PB}	$.5 \times 10^{-6}$ - 5×10^{-6}	10^{-7}	Volt-Sec/Amp	Constant
L_{SSB}	$.5 \times 10^{-6}$ - 5×10^{-6}	10^{-7}	Volt-Sec/Amp	Constant
L_{ℓ}	$.5 \times 10^{-6}$ - 5.0	Factors of Ten	Volt-Sec/Amp	Variable
K	.80 - .96	.01	Dimensionless	Variable

DISTRIBUTION

INTERNAL

DIR
DEP-T
R-DIR
R-AERO-DIR
-S
-SP (23)
R-ASTR-DIR
-A (13)
R-P& VE-DIR
-A
-AB (15)
-AL (5)
R-RP-DIR
-J (5)
R-FP-DIR
R-FP (2)
R-QUAL-DIR
-J (3)
R-COMP-DIR
R-ME-DIR
-X
R-TEST-DIR
I-DIR
MS-IP
MS-IPL (8)

EXTERNAL

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